Neutral Transport Simulations of Gas Puff Imaging Experiments on Alcator C-Mod

D. P. Stotler, B. LaBombard[1],
J. L. Terry[1], and S. J. Zweben

Princeton Plasma Physics Laboratory
Princeton University
Princeton, NJ 08543

[1]MIT Plasma Science and Fusion Center
Cambridge, MA 02139

Note: This poster is available on the Web at:
http://w3.pppl.gov/degas2/

INTRODUCTION

- Tokamak edge ideal for comprehensive study of turbulence,
  - Accessible with probes
    $\Rightarrow$ directly measure n_e, T_e, and other properties.
  - Relatively low T_e facilitates use of atomic physics as basis for diagnostics.
  - Potential payoff great because edge sets boundary conditions for core transport,
    - E.g., internal transport barriers, H-mode pedestal.
- Gas Puff Imaging (GPI) experiments designed to measure 2-D structure of edge turbulence,
  - Compare with 3-D nonlinear simulations.
  - And with turbulence measured by probes,
  - Puff neutral gas (e.g., D_2) near outer wall,
    - View with fast, high res. camera light from electron impact excitation of gas,
    - Use sightline $\parallel \vec{B}$ to see radial & poloidal structure,
- Explore relation between images & plasma fluctuations with DEGAS 2 neutral transport code,
  - Straightforward because puff does not perturb plasma,
  - Emitted light brighter than background,
  - Material surface interactions should not be important.
- Experimental presentation: O-02 J. L. Terry et al.

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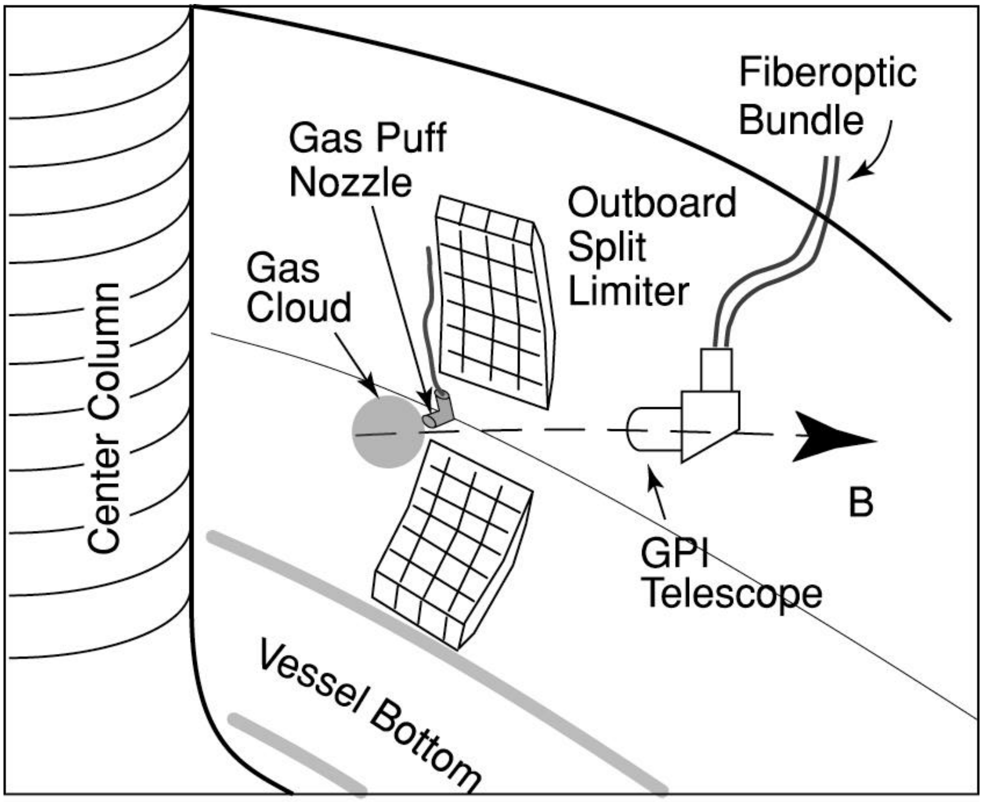
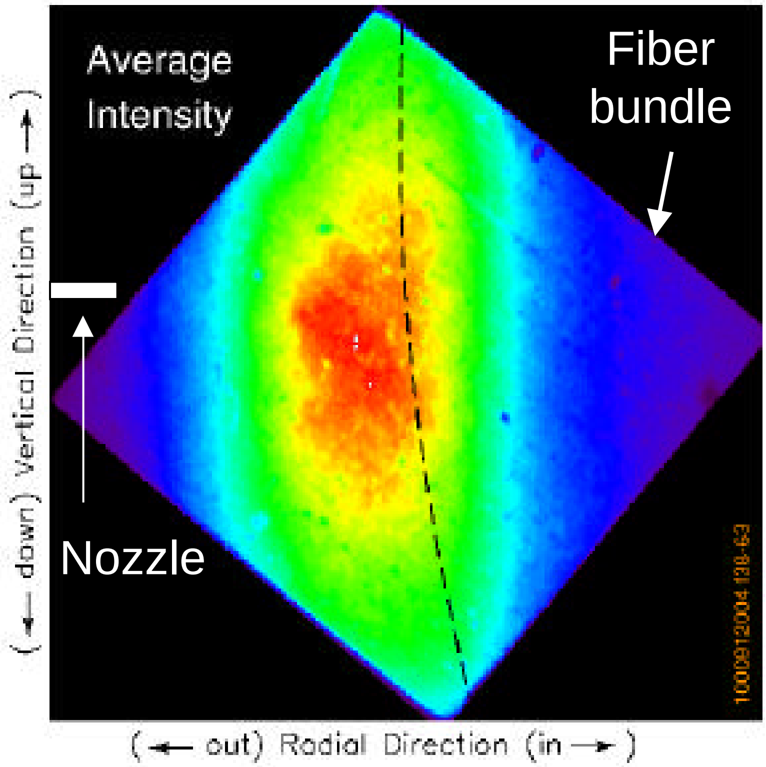


Fig. 1 - Zweben APS ‘01



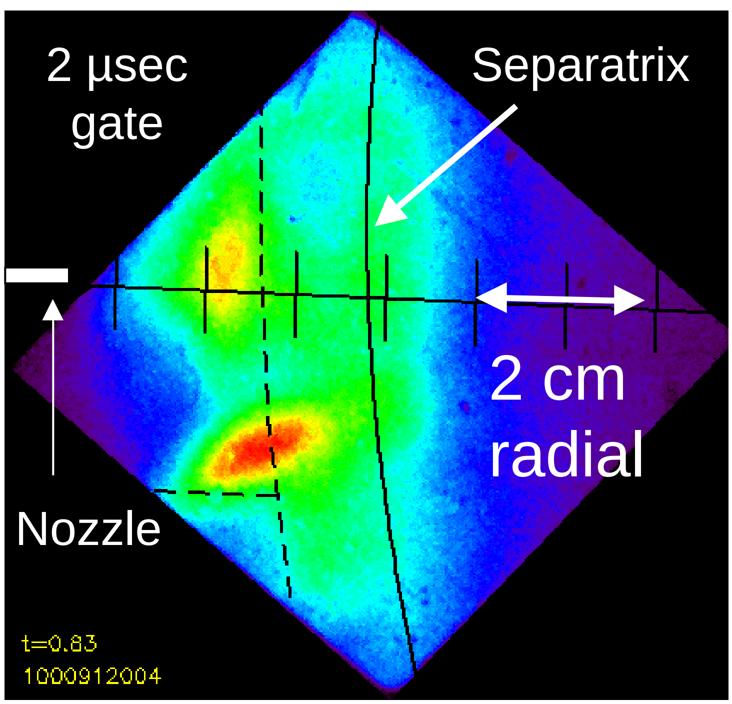
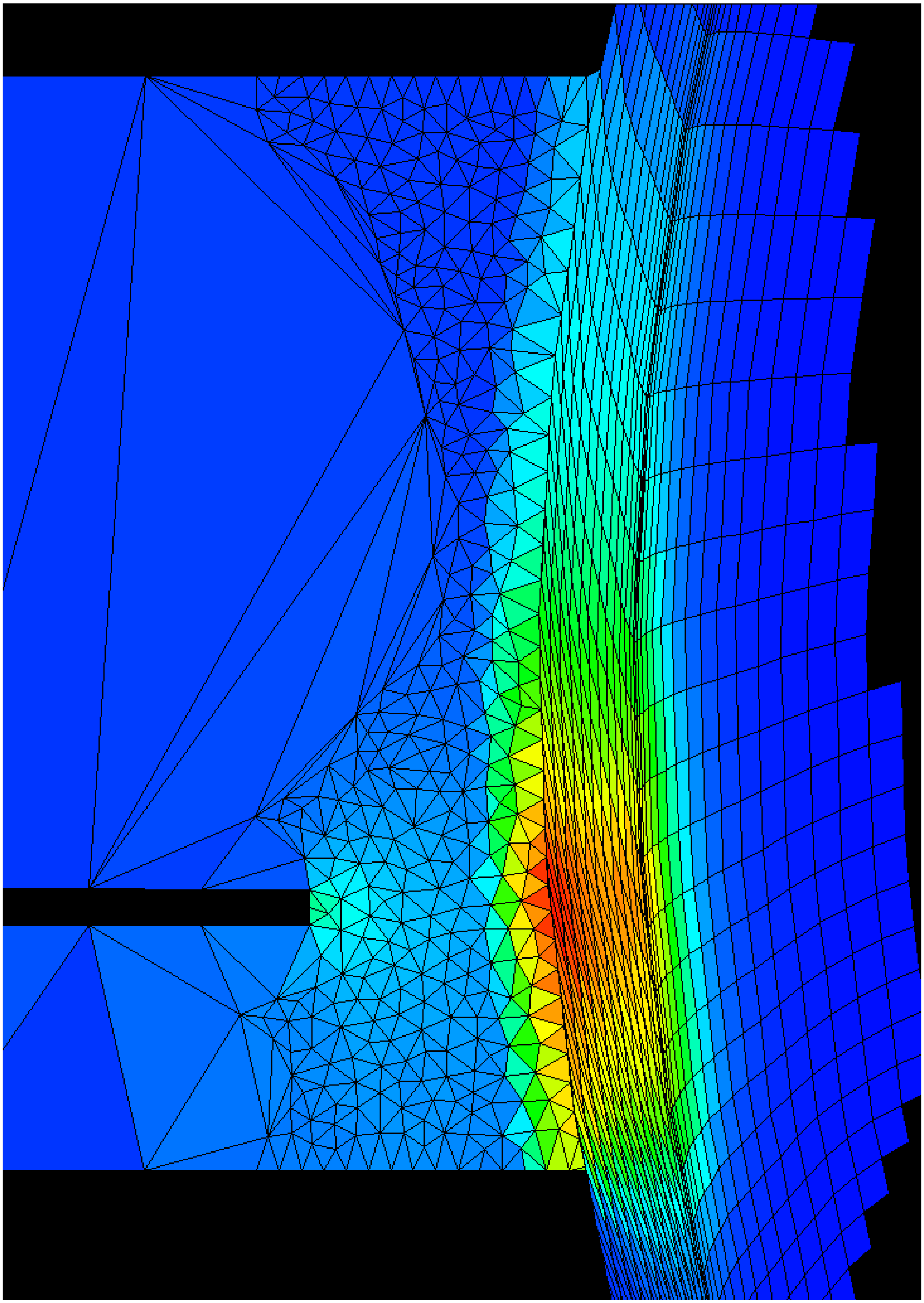


Fig. 2 - Zweben / APS '01

DESCRIPTION OF DEGAS 2 SIMULATIONS

- Alcator C-Mod Geometry:
  - Start with outline of vacuum vessel,
    - Including gas puff nozzle & surrounding structures.
  - EFIT equilibrium for time of interest $\Rightarrow$
    - 2-D plasma mesh set up using `DG` & `Carre`,
    - Bunch surfaces & grid points to get resolution 3 mm or smaller in region of interest.
  - Divide puff region into ~ 3 mm triangles using `Triangle`.
- Simulations 2-D axisymmetric for now,
  - Output is averaged over toroidal angle.
  - $\Rightarrow$ poloidal plane variation of photon emission rates.
  - Plan to add toroidal resolution $\Rightarrow$
    - Can directly simulate fast camera views,
    - Quantitative comparison of image intensity,
    - Evaluate toroidal spatial averaging.

DEGAS 2 Geometry for C-Mod Shot 1010622



- Simulations assume steady-state.
  - Compare time scales:
    - Autocorrelation time for turbulence = 10 – 20 μs,
    - Time for 3 eV D to travel across cloud = 1 μs (2 cm),
    - Timescale for emission of D_α photon $= 1/A_{3\rightarrow 2} = 0.02$ μs,
    - Note that camera exposure times = 2 μs (60 frame/s) or 4 μs (5×10^6 frames / s),
    - $\Rightarrow$ assumption of stationary plasma OK.

- Physics:
  - D_2, D_2^+ dissociation, including
    - $e + D_2 \rightarrow e + D(1s) + D(1s)$
    - $e + D_2 \rightarrow e + D(1s) + D^*(n = 3)$
    - $e + D_2 \rightarrow 2e + D_2^+$
    - $e + D_2 \rightarrow 2e + D(1s) + D^+$
    - $e + D_2^+ \rightarrow 2e + 2D^+$
    - $e + D_2^+ \rightarrow e + D(1s) + D^+$
    - $e + D_2^+ \rightarrow e + D^+ + D^*(n = 3)$
    - $e + D_2^+ \rightarrow D(1s) + D^*(n = 3)$
  - D + D^+ elastic scattering (i.e., charge exchange),
  - D_2 + D^+ elastic scattering,
  - e + D ionization,
    - "Multi-step", i.e., collisional-radiative model.
  - Neutral-neutral collisions *not* included,
    - May not be negligible,
    - Need realistic neutral density to treat,
    - Can only be computed in 3-D.

– Emission rate (m^{-3} s^{-1}) written as:

$$S_{\mathrm{D}_\alpha} = \sum_{j=\mathrm{D},\mathrm{D}_2,\mathrm{D}_2^+} n_j f_j(n_e, T_e),$$

∗ Where $n_j =$ ground state atom & molecule density,

$$f_D = \frac{n_D(n=3)}{n_D(n=1)} A_{3\rightarrow 2},$$

∗ $[n_D(n=3)/n_D(n=1)](n_e, T_e)$ from CR model,

∗ Largely determines n_e, T_e dependence of f_D.

$$f_{D_2}, f_{D_2^+} = n_e \sum_k \langle \sigma v \rangle_k (T_e),$$

∗ $k =$ reactions leading to $n = 3$.

– All puffs are 300 K with cosine distribution,

∗ Examined sensitivity in preliminary runs,

∗ Run with $(\cos\theta)^4$ distribution,

∗ One with 150 K puff.

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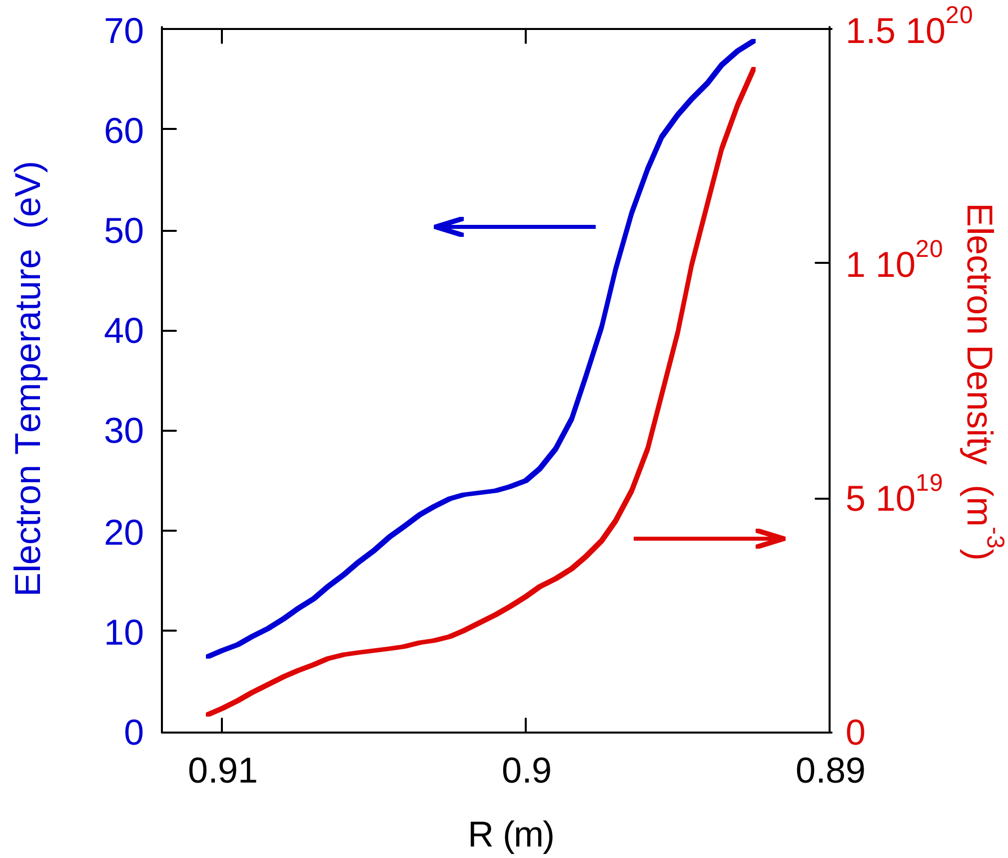
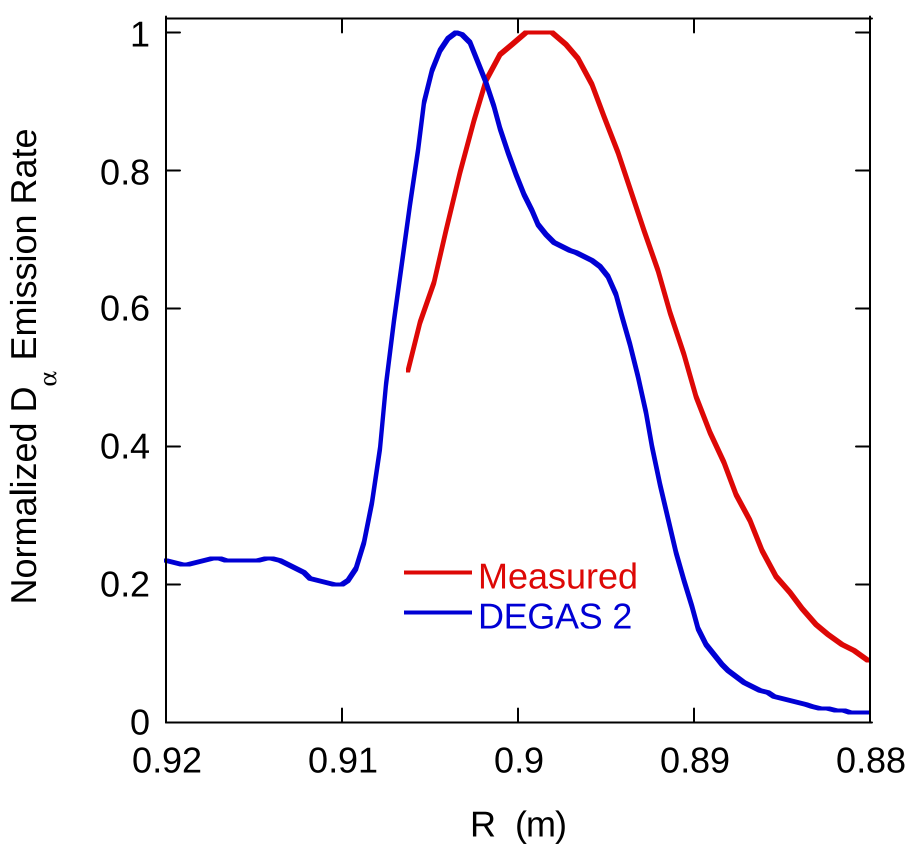
- Plasma profiles:
  - All are taken from measured data mapped to midplane,
  - Assume constant on a flux surface,
    - In triangulated region, estimate $\rho =$ distance between zone center & nearest flux surface mesh zone.
  - Assume $n_i = n_e$, $T_i = T_e$.

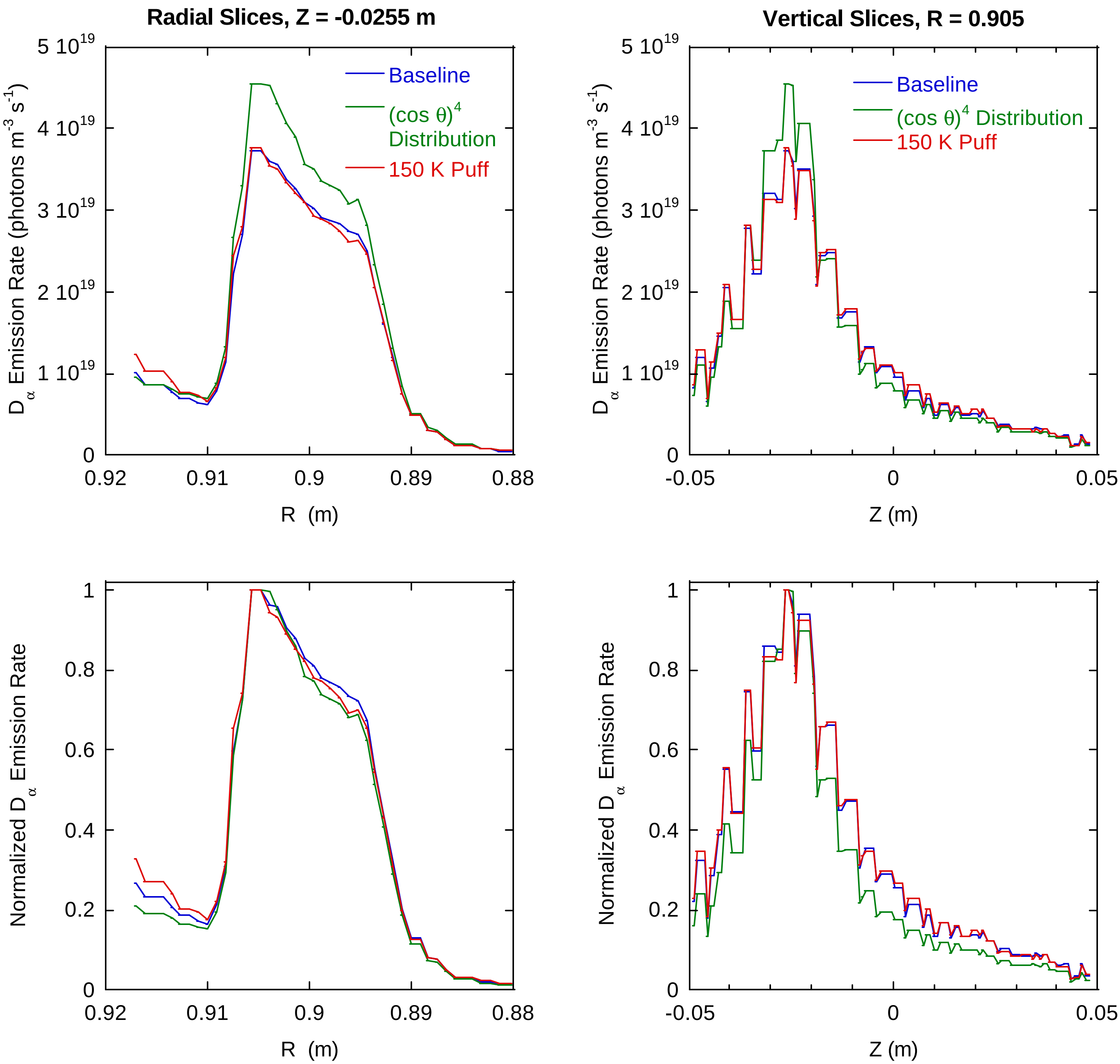
Scanning Probe Data from C-Mod
Shot 1010622006, 700 ms



Compare DEGAS 2 Result with Experimental Data
Radial Slice at Z = -0.034 m



Peak Location & Width of Simulated Emission Insensitive to Details of D_2 Distribution



⇒ Vertical extent can be affected

C-MOD RESULTS

- Alcator C-Mod shot 1010622006 at 700 ms.
- Baseline computed with time-average plasma profiles,
  - 10 – 20% of atoms in cloud undergone reflection,
  - "CX fraction" have had a CX,
  - Rest from dissociation $\Rightarrow$ ballistic trajectories.
  - $\Rightarrow \sim 50 - -65\%$ of D emission
- At peak, molecular D$_\alpha$s contribute $\sim 40\%$,
  - $< 10\%$ for $R \lesssim 0.9$ m.
- Compare with time-average experimental GPI images,
  - Emission peak near nozzle not seen experimentally,
  - Probe data assumed constant for $R > 0.91$ m,
  - Nozzle peak $\downarrow 10^{-2}$ if $T_e < 2.5$ eV
  - Or if $n_e < 3.6 \times 10^{16}$ m^{-3},
  - Both consistent with exponential extrapolation of probe data.

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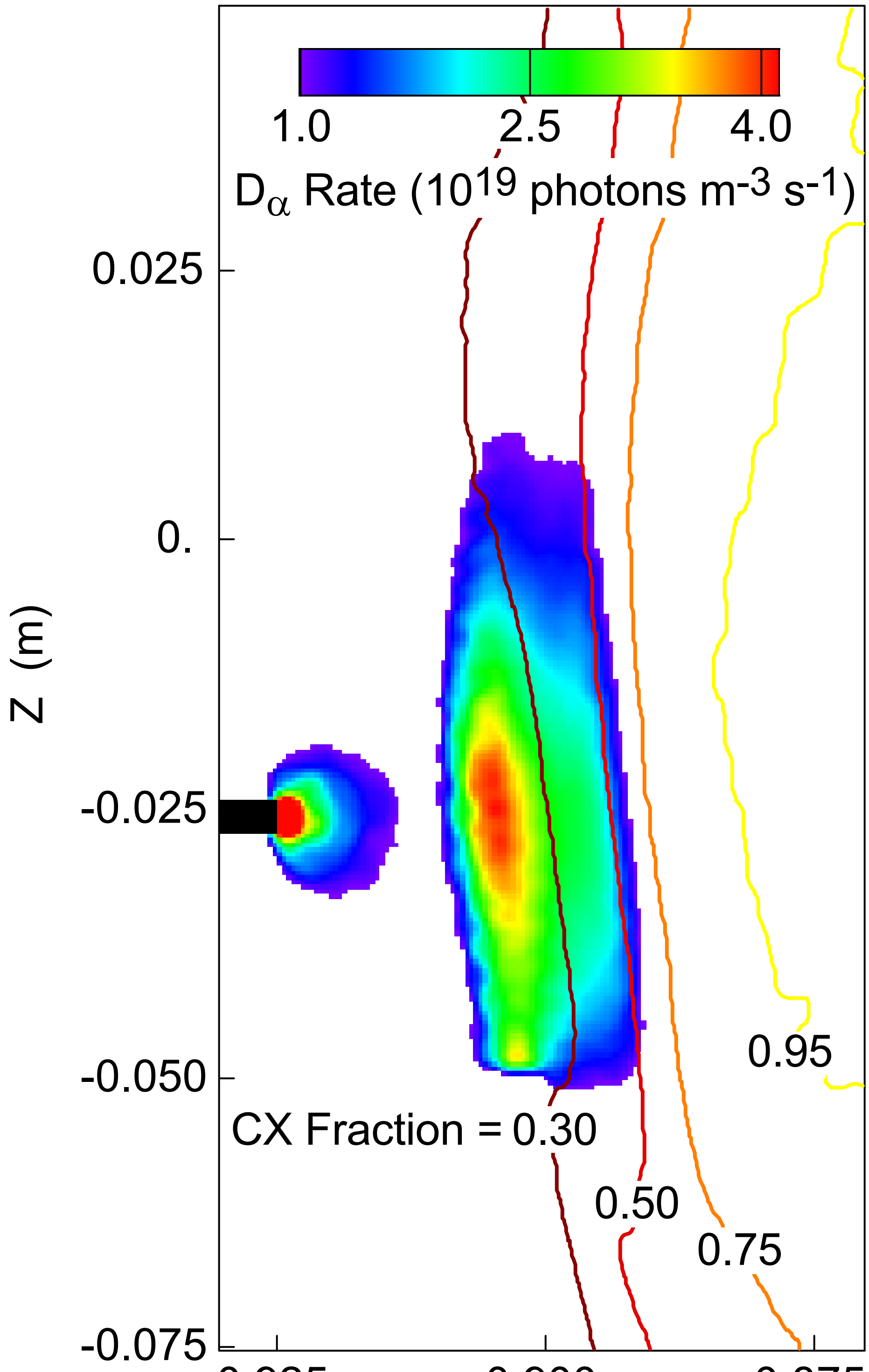
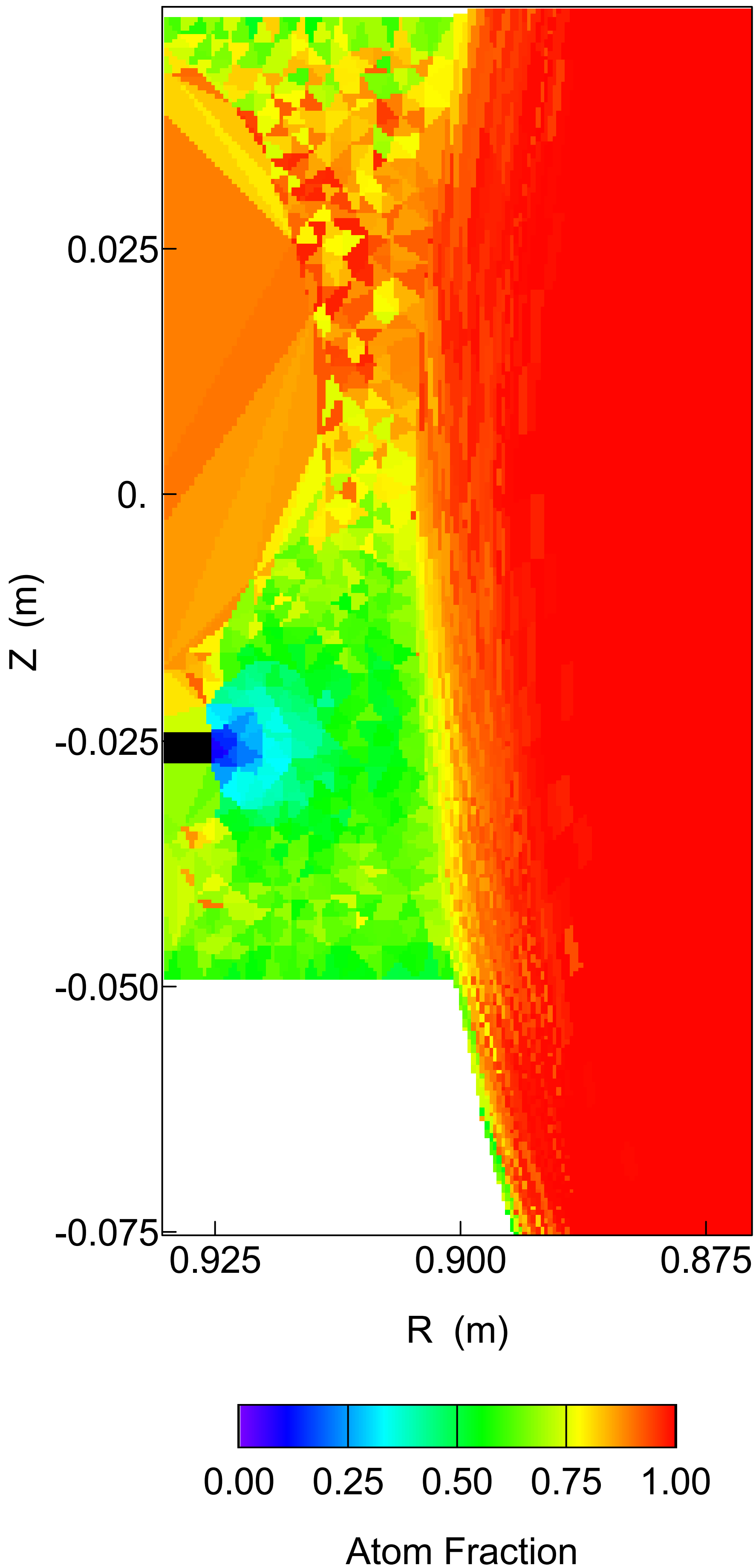
DEGAS 2 Baseline



Fraction of D_α Due to Atoms



- Impose 2-D perturbation on n_e and T_e,
  - Important to understand relation between spatial variation in emission & underlying plasma fluctuations,
  - Consider ad hoc perturbation:

$$\begin{aligned} n_e'(R,Z) &= n_e(R,Z)[1+\frac{1}{2}\sin(\frac{\pi Z}{0.01})] \\ &\times\{1+\frac{1}{2}\sin[\frac{\pi(R-R_{\mathrm{sep}}+0.0035)}{0.005}]\}, \end{aligned}$$

  - where:
    - The $1/2$ factors make this a 50% perturbation,
      - Factor ranges from 0.25 to 2.25.
    - 2 cm wavelength for poloidal ($\sim Z$) variation,
      - Typical size of observed emission structures.
    - Used only 1 cm in R because of limited radial width,
      - 0.0035 shift so innermost data point unchanged.
  - Try same perturbation on T_e,
    - Only difference: T_e bound between 5 and 100 eV.

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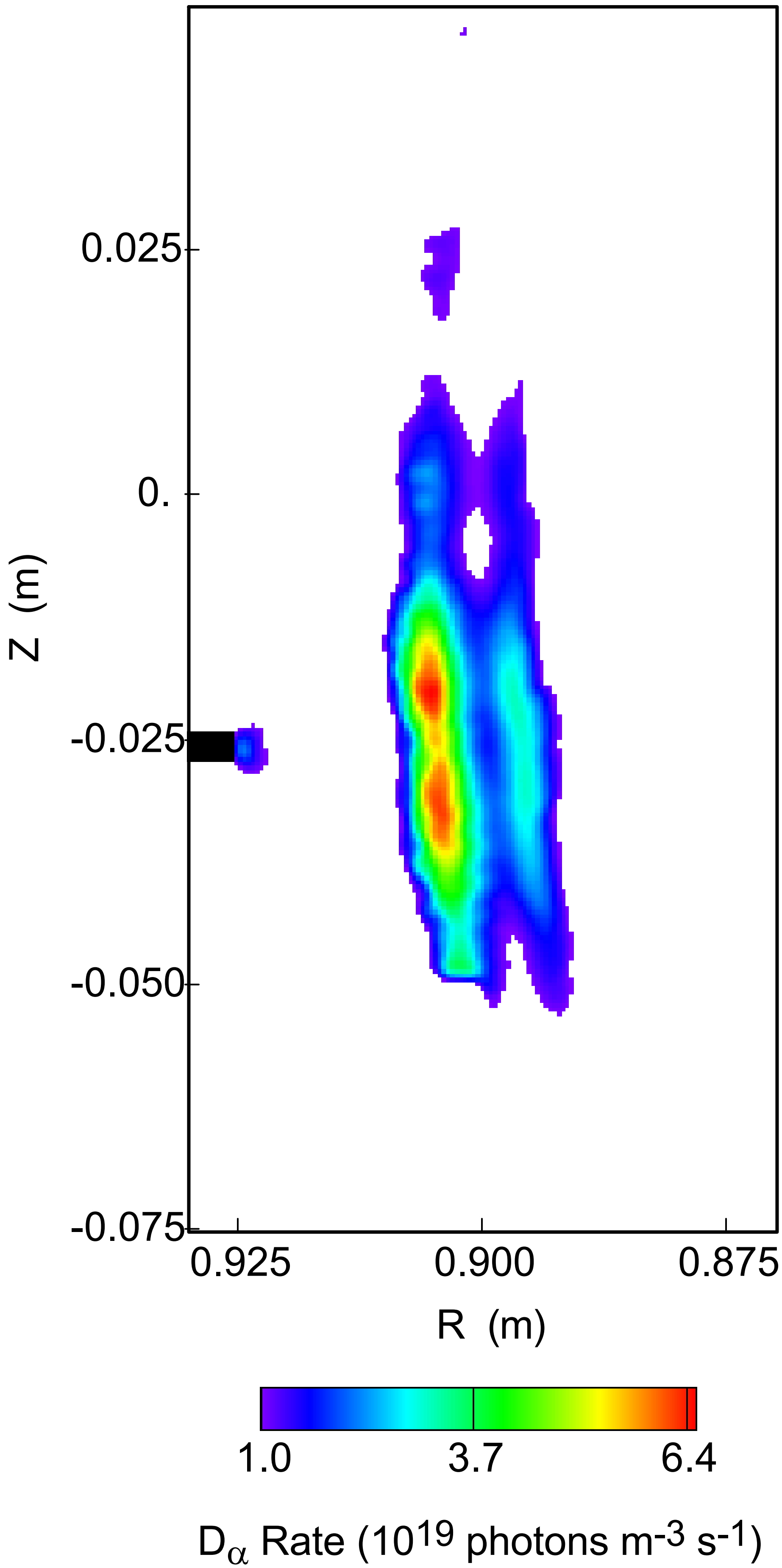
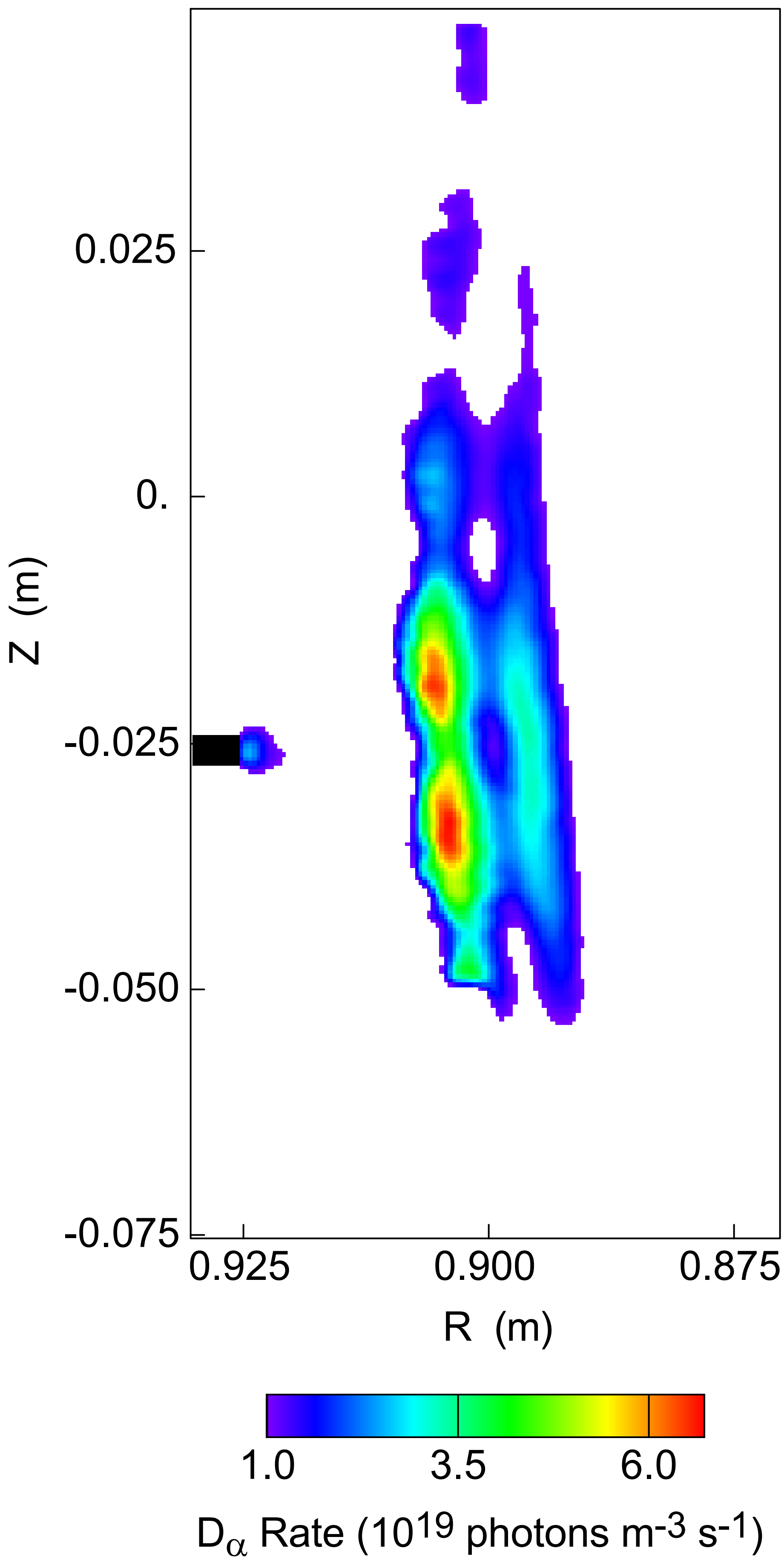
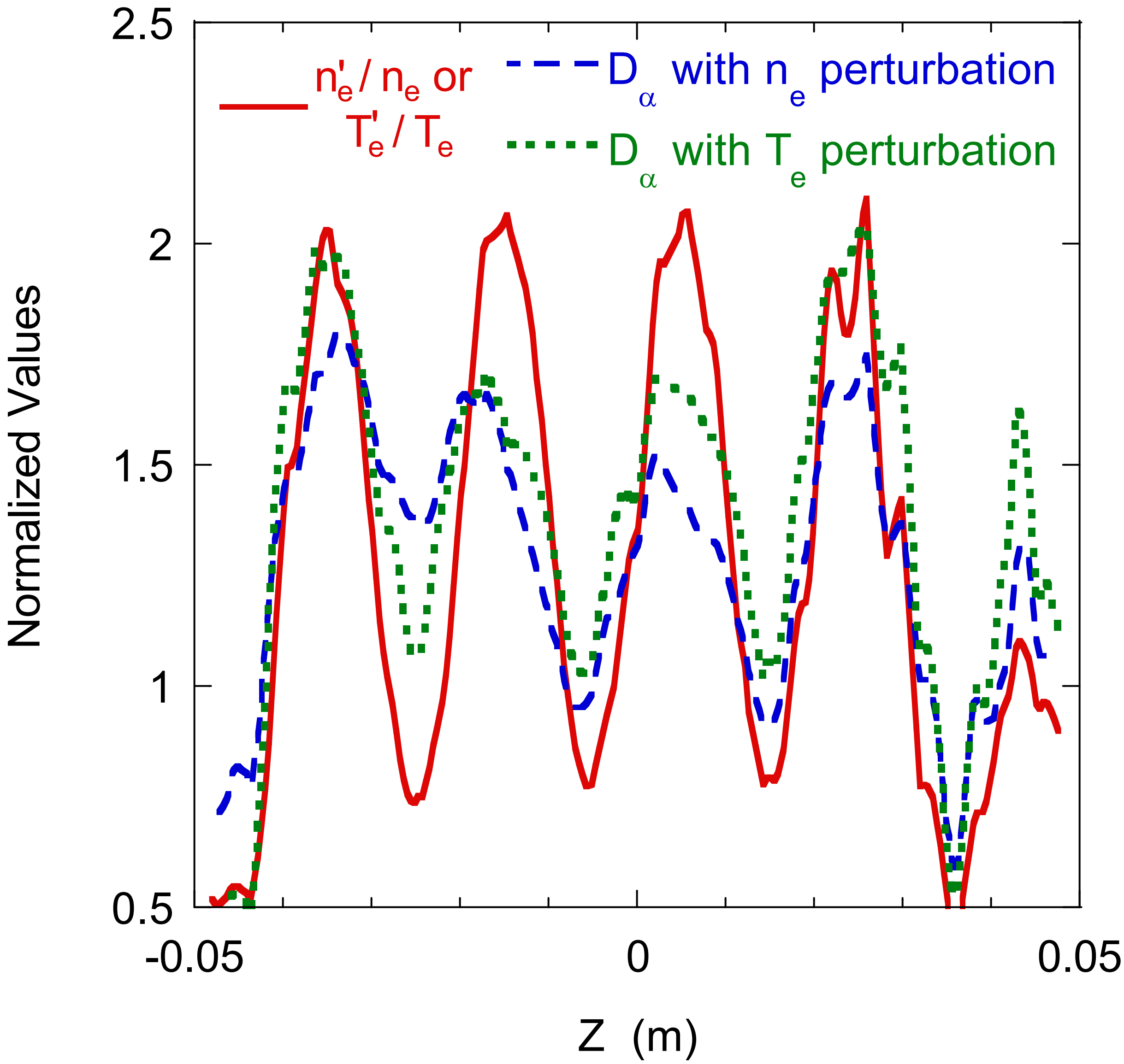
2-D Perturbation to Electron Density



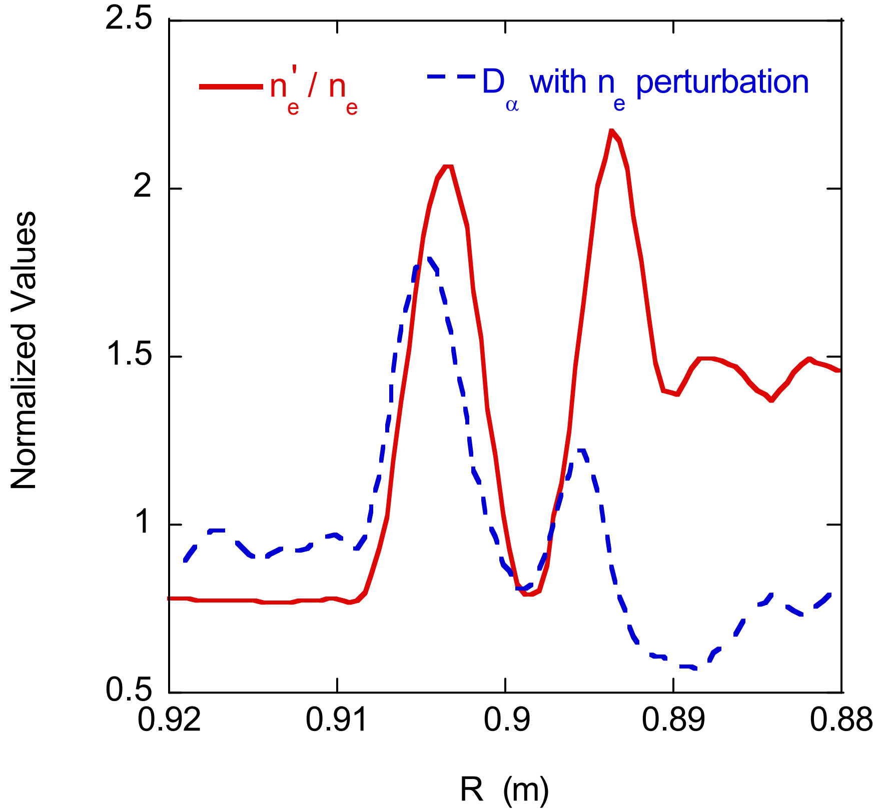
2-D Perturbation to Electron Temperature

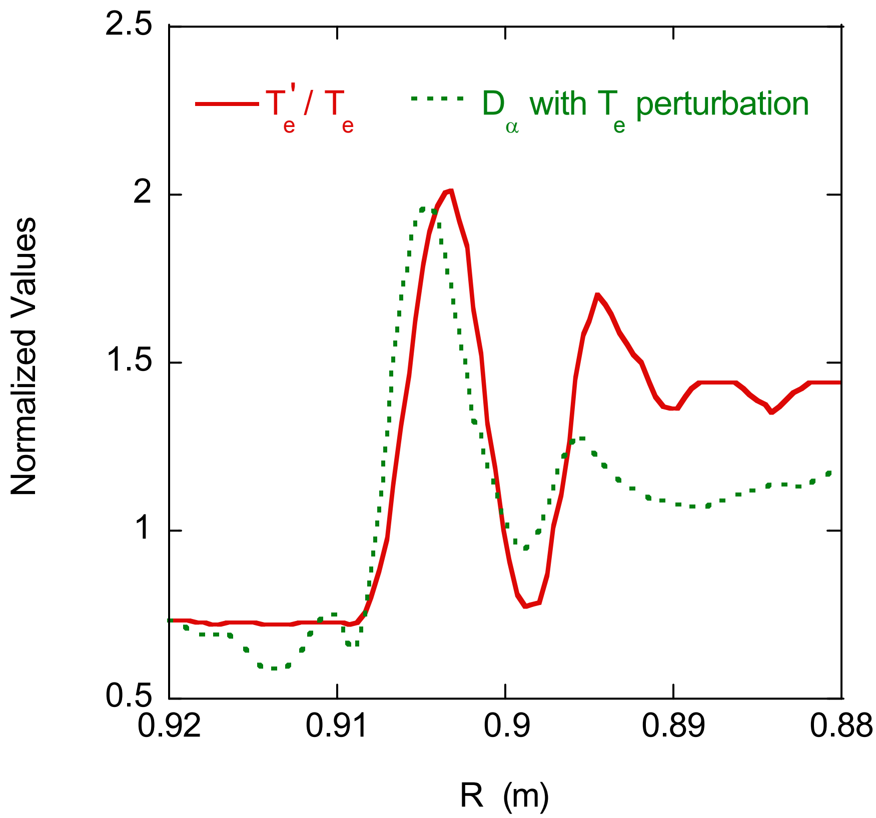


Effect of 2-D Perturbation Normalized to Unperturbed Value Vertical Slice



Effect of 2-D Perturbation Normalized to Unperturbed Value Radial Slice





- Both simulations shows same 2-D structure,
- $\Rightarrow$ wavenumber spectrum at least similar to that of plasma turbulence,
  - Expect autocorrelation function & frequency spectra similar also,
  - Will subsequently investigate quantitatively.
- Ratio of perturbed / unperturbed emission $\neq n_e'/n_e$ because $\partial \ln f_{\mathrm{D}} / \partial \ln n_e$, $\partial \ln f_{\mathrm{D}} / \partial \ln T_e < 1$.
- Further complicated by molecular contributions,
  - f_{D_2} and $f_{\mathrm{D}_2^+} \propto n_e$,
  - T_e dependence not simple,
  - Effective scaling varies radially.

- Simple interpretation of GPI: image patterns $\propto n_e'/n_e$,
  - And insensitive to T_e,
  - Valid only if $n_e \lesssim 10^{18}$ m^{-3} and $T_e \gg 10$ eV,
  - Not the case here!
  - $\Rightarrow n_e$, T_e dependence of S_{D_α} not different enough to infer perturbation amplitudes,
  - Would be simpler if n_e, T_e in phase.

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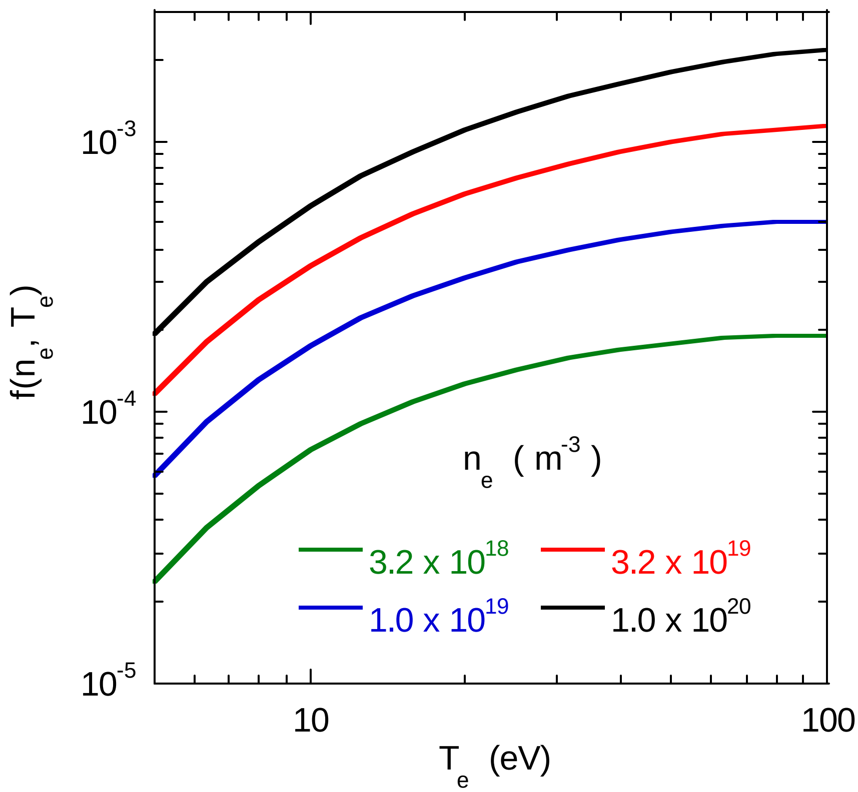
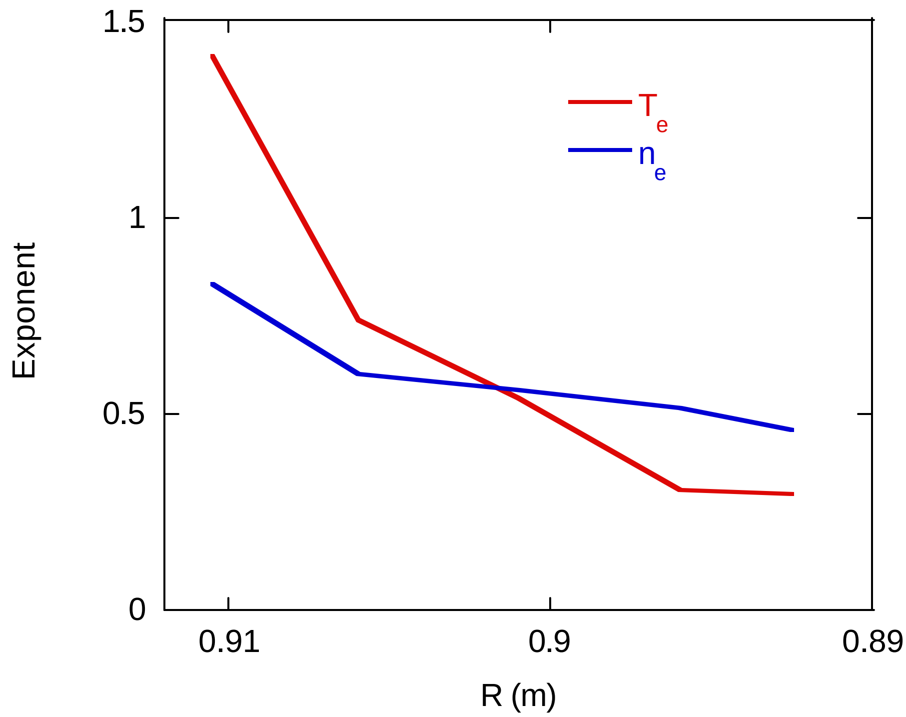
n_e, T_e Dependence of D_a Emission Rate Contained in Ratio of n=3 Density to n=1



Scaling of $f(n_e, T_e)$ Varies Across Radial Profiles of 1010622



Shadow Fraction

- Above focussed only on effect of perturbation on f_j,
- They also impact n_j!
- "Shadowing effect": ionization caused by local n_e, T_e peak reduces light at smaller R.
- Compare images with and without shadowing,
  - "With" shadowing is as above,
  - To eliminate, use perturbed f_j and *unperturbed* n_j,
  - "Unshadowed" clearly shows n_e perturbation structure,
  - Shadowed image smeared out,
    - Due to n_j reductions by n_e peaks,
    - And n_j *increases* by n_e minima.

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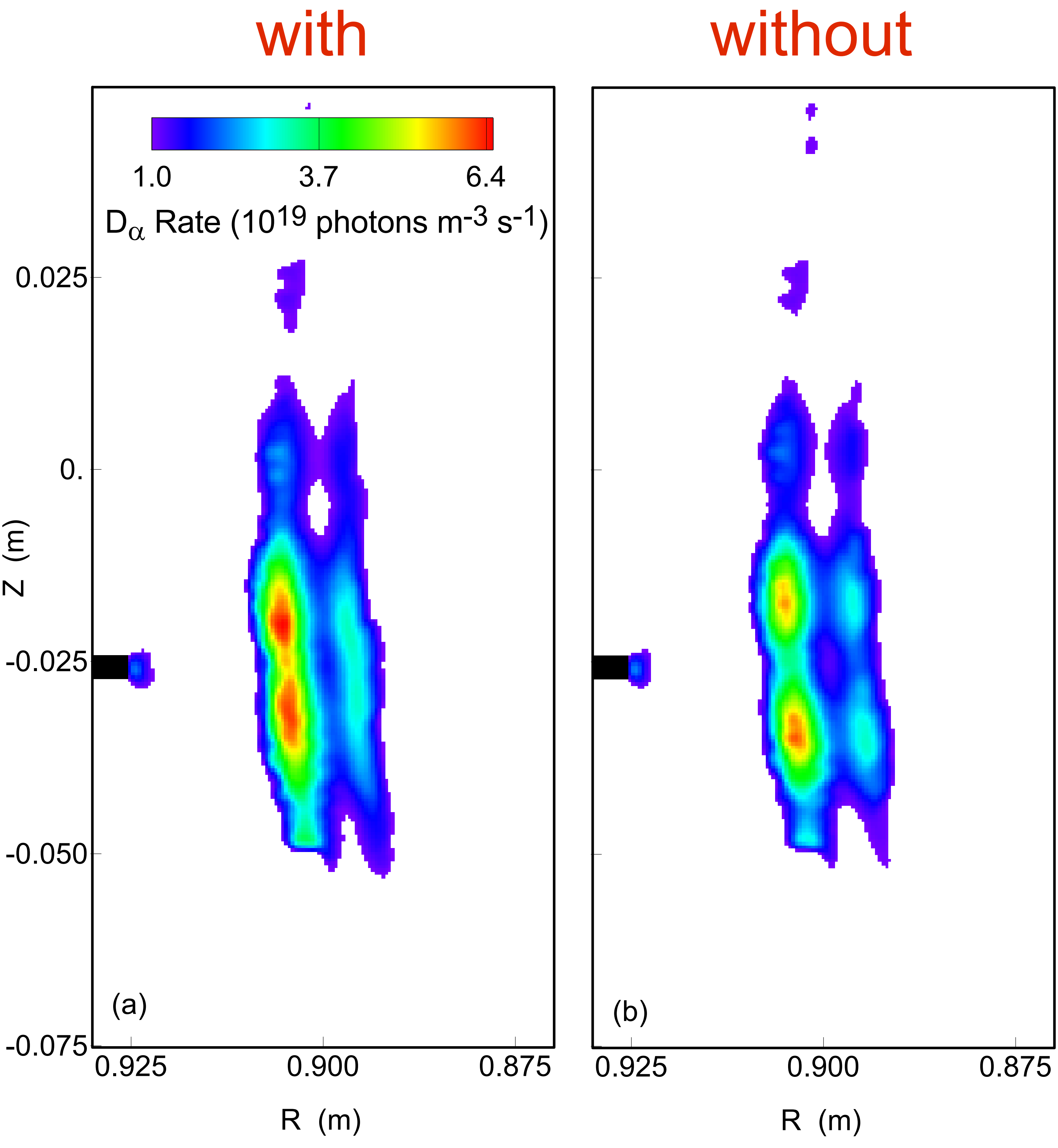
Runs with Electron Density Perturbation

Shadowing:



- Estimate by computing:

$$F_s = \left[\sum_j (n'_j - n_j) f'_j\right] / \sum_j n_j f_j,$$

  - Where prime indicates perturbed value.
  - Evaluate separately for both "perturbed" simulations.
- Structure is complicated!
- Main observations:
  1. $|F_s| \gtrsim 0.5$ in many places
     $\Rightarrow$ too large to ignore in GPI analysis.
  2. Most of F_s due to molecules,
     - Analogous quantity based on atoms only ≤ 0.2.
- To understand F_s look at radial slices,
  - $Z = -0.034$: peak in n'_e/n_e,
  - $Z = -0.025$: at nozzle & a minimum in n'_e/n_e.
  - Compare with $1 - n'_e/n_e$,
    * $1 - n'_e/n_e < 0 \Rightarrow$ local $n_e >$ unperturbed value,
    * $1 - n'_e/n_e > 0 \Rightarrow$ local $n_e <$ unperturbed value,
    * T_e perturbation differs at edges.
  - $F_s < 0 \Rightarrow n_j$ locally reduced,
    * F_s drops are in "shadows" of largest n'_e/n_e.
  - $F_s > 0 \Rightarrow n_j$ locally increased,
    * $F_s > 0$ at $Z = -0.025$ since n_e modulation near min.,
    * Not so in perturbed T_e case due to smaller dissociation rate & strong T_e dependence of f_j.

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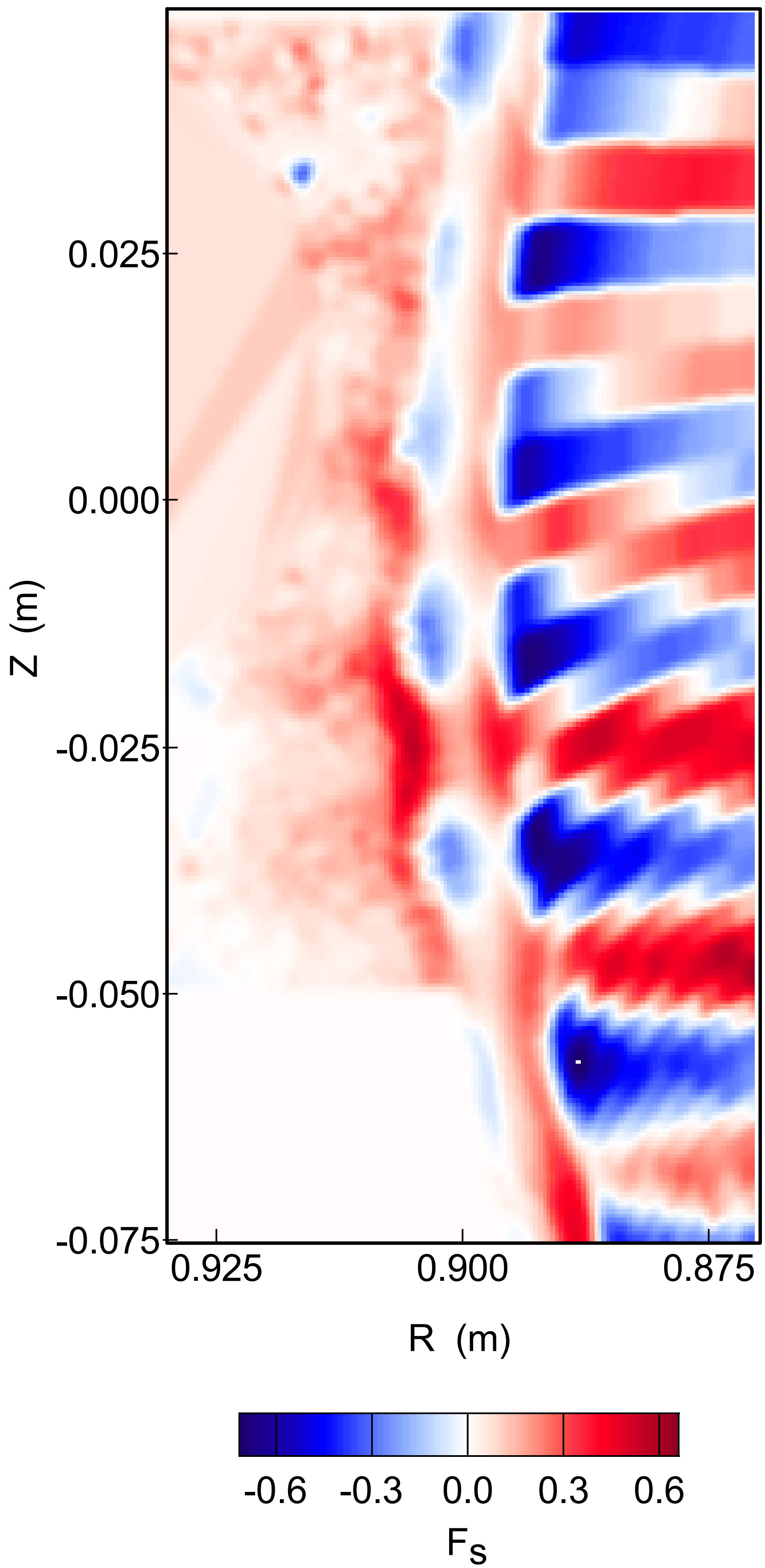
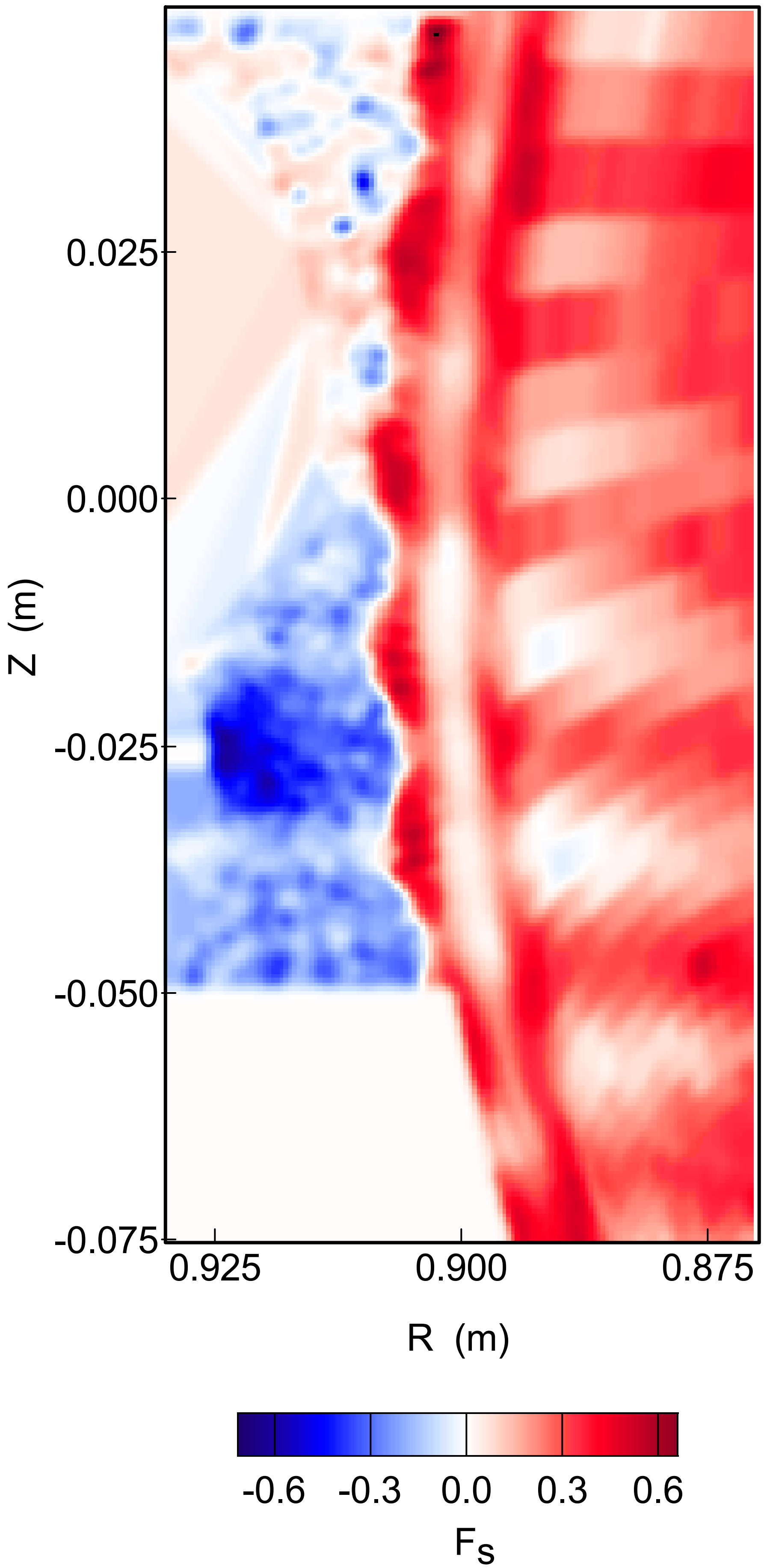
Shadow Fraction with Density Perturbation

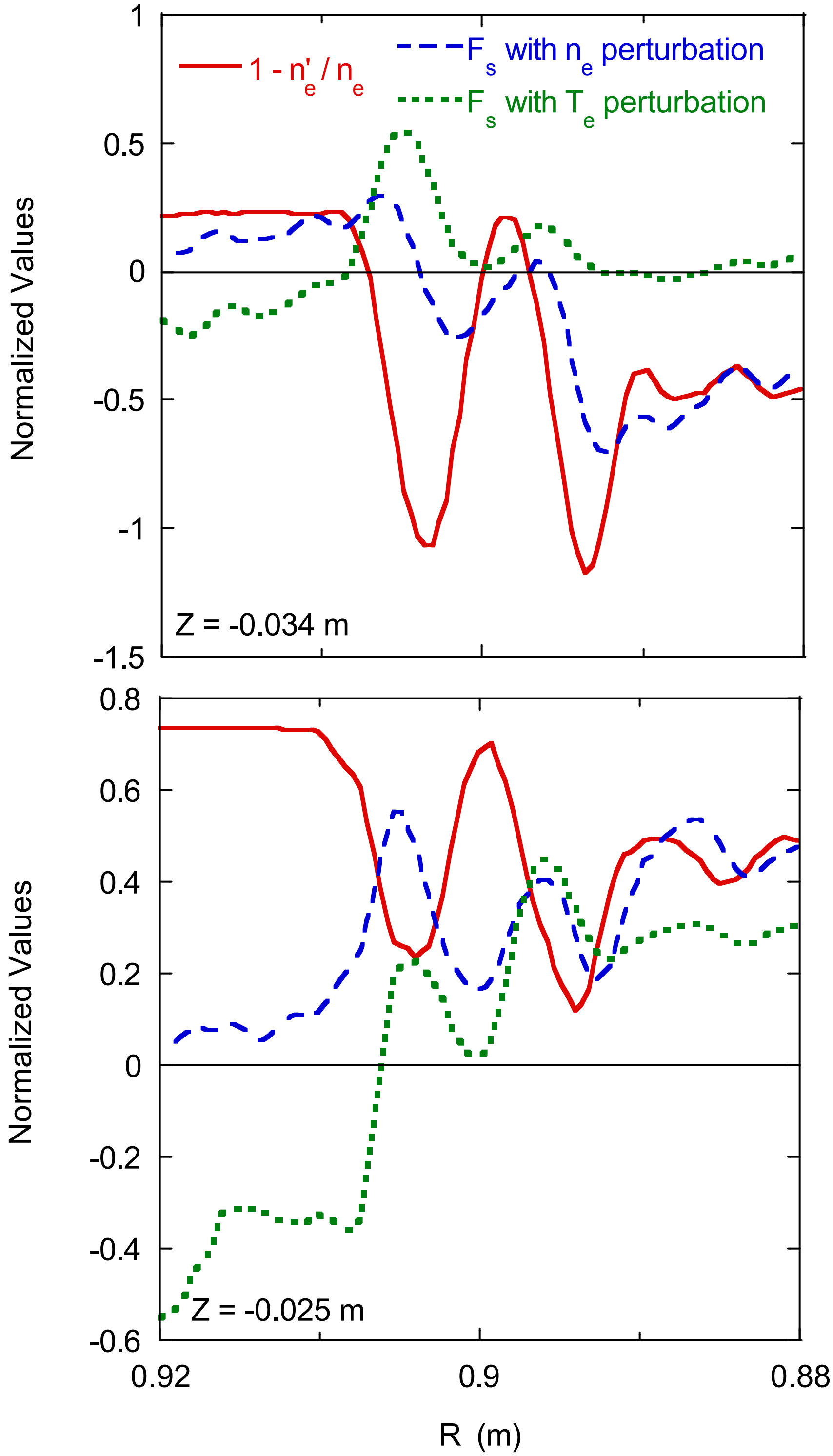


Shadow Fraction with Temperature Perturbation



Shadow Fraction Significant

Radial Slices



CONCLUSIONS

- DEGAS 2 simulations show that spatial variation of D_α emission reflects that of n_e, T_e turbulence.
- But, n_e, T_e dependence of emission rate complicated,
  - $\Rightarrow$ no simple scheme to get plasma fluctuations.
- Contributions from molecules significant,
  - Further complicating n_e, T_e dependence,
  - Densities significantly affected by perturbation.
- $\Rightarrow$ will need neutral transport code to interpret GPI,
  - Must do careful benchmarks first,
  - To verify these conclusions,
  - Validate atomic & molecular physics models.